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(54) Title: METHOD AND APPARATUS FOR DIGITAL COMPENSATION OF RADIO DISTORTION IN A WIRELESS COMMUNICATION SYSTEM

(57) Abstract

Radio distortion in a radio signal is compensated for in a digital modem in a wireless communication system. An actual frequency response of components in the wireless communication system contributing to distortion is determined. The inverse of the actual frequency response is multiplied with an ideal frequency response of the wireless communication system to produce a compensation frequency response. The compensation frequency response is applied to the radio signal to compensate for radio distortion. Alternately, an actual impulse response of components in the wireless communication system contributing to distortion is determined. The actual impulse response is convolved with an input reference signal to produce an actual output signal. The ideal impulse response is convolved with the same input reference signal to produce a desired output signal. The actual output signal is subtracted from the desired output signal to produce an error signal, and an adaptive algorithm is applied to the error signal to produce an adaptive compensation impulse response. When the adaptive compensation impulse response converges to an optimal solution, it is applied to the radio signal to compensate for radio distortion.

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METHOD AND APPARATUS FOR DIGITAL COMPENSATION OF RADIO DISTORTION IN A WIRELESS COMMUNICATION SYSTEM

Field of the Invention

The present invention relates generally to a digital signal processing method and apparatus for a wireless communication system. More particularly, the present invention relates to a method and apparatus for digitally compensating for radio distortion in a wireless communication system.

Background of the Invention

In any wireless communication system, various distortions are generated during signal transmission and reception. Such distortions may be caused by various components in the reception and transmission paths or by the radio-air interface. These distortions can significantly degrade communication system performance if not properly compensated.

Figure 1 illustrates a typical wireless communication system. A signal to be transmitted is encoded in a Source Encoder 100 and a Channel Encoder 200, then modulated in a Digital Modulator 300. The encoded signal can be modulated according to any known modulation technique. For example, in the Personal Wireless Telecommunications Interoperability Standard (PWT), as described in Part 2: Physical Layer, TIA/EIA 662-2, a signal is $\pi/4$ Differential Quadrature Phase Shift Keyed (DQPSK) modulated. The Digital Modulator 300 is typically implemented in a digital modem. The modulated signal is then passed through a Transmission Channel 400 before being transmitted through the air via an Antenna 500. A series of bandpass filters are typically employed in the Transmission Channel 400 to assure that the signal to be transmitted is confined within a pre-defined frequency band with appropriate transmit characteristics.

The transmitted signal is received at an Antenna 600, processed through a Receiving Channel 700, which has similar circuitry as the Transmission Channel 400, demodulated in a Digital Demodulator 800, and decoded in a Channel Decoder

900 and a Source Decoder 1000. Ideally, the output from the Source Decoder 1000 is the same as the input to the Source Encoder 100.

Figure 2 illustrates a detailed block diagram of the Transmission Channel 400. As shown in Figure 2, the Transmission Channel 400 includes a D/A Converter 410, Intermediate Frequency (IF) Bandpass Filters 420 and 440, Mixers 430 and 450, and a Radio Frequency (RF) Front End 460. The IF Filters 420 and 440 confine the signal to a particular frequency band, the Mixers 430 and 450 up convert the baseband modulated signal to an intermediate frequency, and the RF Front End 460 converts the up converted signal to a radio frequency. The IF Filter 420 is typically an interstage filter that is centered, for example, at 11.25 MHZ, and the IF Filter 440 is typically a SAW filter that is centered, for example, at 422.5 MHZ.

The IF Filters 420 and 440 are typically designed with analog components or surface acoustic wave technology. Due to their analog nature, the IF Filters 420 and 440 often produce imperfect frequency responses which cause channel distortion. The channel distortion degrades the quality of the transmitted signal.

Reducing channel distortion to a reasonable level has always been a great challenge in wireless communication system design. Traditionally, the problem of radio channel distortion has been solved by simply putting more restrictive requirements on the analog filter design in the transmission channel. However, the design of a perfect analog filter that meets radio transmission requirements can be technically difficult. This often results in more expensive components and a longer design cycle. It is often not feasible to obtain an optimal analog filter design due to cost and time constraints.

Digital compensation provides an attractive alternative. For example, the Digital Cordless Telephone (DCT) 1900 modem includes a digital compensation filter. However, this filter is primarily concerned with compensating distortion due to signal digitization.

It would be desirable to provide a digital compensation filter for a wireless communication system which compensates for radio distortion without requiring additional hardware.

Summary of the Invention

The present invention overcomes the above-described problems, and provides additional advantages, by providing a method and apparatus for digitally compensating for radio channel distortion in a radio signal in a wireless communication system. According to an exemplary embodiment of the present invention, digital compensation is performed in digital ~~modem ASIC~~ circuitry in the wireless communication system.

According to a first embodiment, the actual frequency response of components in the wireless ~~communication system~~ contributing to distortion is determined. The inverse of the actual frequency response is multiplied with a desired frequency response of the wireless communication system to produce a compensation frequency response. The compensation frequency response is applied to the radio signal to compensate for radio distortion.

According to a second embodiment, the actual impulse response of components in the wireless ~~communication system~~ contributing to distortion is determined and convolved with an input reference signal to produce an actual output signal. A desired system impulse response is convolved with the same input reference signal to produce a desired output signal. The actual output signal is subtracted from the desired output signal to produce an error signal. An adaptive algorithm is applied to the error signal to produce an adaptive compensation impulse response. The adaptive compensation impulse response is convolved with the input reference signal and the actual impulse response to produce an updated actual output signal, and the updated actual output signal is subtracted from the desired output signal to produce an updated error signal. The adaptive algorithm is applied to the updated error signal to form an updated adaptive compensation impulse response. The adaptive compensation impulse response is updated, the updated adaptive compensation impulse response is convolved with the actual impulse response and the input reference signal to produce the updated output signal, and the updated actual output signal is subtracted from the desired output signal to produce the updated error signal until the adaptive compensation impulse response converges to an optimal solution. Then, the adaptive compensation impulse response is applied to the radio signal to compensate for radio distortion.

Brief Description of the Drawings

A more complete understanding of the present invention can be obtained upon reading the following Detailed Description of the Preferred Embodiments, in conjunction with the accompanying drawings, in which like reference numbers are used to designate like elements, and in which:

Figure 1 illustrates a block diagram of a typical wireless communication system;

Figure 2 illustrates a detailed block diagram of a radio transmission channel;

Figure 3 illustrates an exemplary radio transmission system employing digital compensation according to the present invention;

Figure 4 illustrates a digital compensation technique using an inverse of an actual frequency response according to a first embodiment of the present invention;

Figure 5 illustrates a digital compensation technique using an adaptive algorithm according to a second embodiment of the present invention; and

Figure 6 illustrates an implementation of the digital compensation technique illustrated in Figure 5.

Detailed Description of the Preferred Embodiments

According to the present invention, a digital compensation method and apparatus are provided in a digital modem for compensating for radio distortion in a radio signal in a wireless communication system. According to exemplary embodiments, distortion caused by filters in the transmission channel in the communication system is digitally compensated for by a digital compensation filter.

Figure 3 illustrates an exemplary radio transmission system employing digital compensation according to the present invention. As shown in Figure 3, a Digital Compensator 350 is included in the transmission system between the Digital Modulator 300 and the Transmission Channel 400. Although shown as a separate device, the Digital Compensator 350 can be included in the Digital Modulator 300.

The Digital Compensator 350 can include a storage device and a digital compensation filter. The storage device stores compensation filter coefficients for the

digital compensation filter. The storage device can be implemented with a memory from which the filter coefficients are downloaded into the digital compensation filter under the control of a microprocessor. Alternately, the storage device can be implemented with hardware components, such as an Application Specific Integration Circuitry (ASIC), which can be included in the digital compensation filter.

According to a first embodiment of the present invention, radio distortion is digitally compensated for by applying a compensation frequency response, which is derived through multiplying a desired system frequency response with a matrix inversion of an actual system frequency response, to the radio signal.

Figure 4 illustrates a technique for digital compensation according to the first embodiment. Referring to Figure 4, ideally the actual output, Y'(f), of the input reference signal, X(f), is the same as the desired output, Y(f). An actual frequency response, an ideal frequency response, and a compensation frequency response of the system are represented in Figure 4 as $H_{radio}(f)$, $H_{desire}(f)$, and $H_{comp}(f)$, respectively.

Assuming that the IF Filters 320 and 340 are the only components contributing to distortion, and their individual frequency responses are $H_{int}(f)$ and $H_{saw}(f)$, respectively, the actual frequency response, $H_{radio}(f)$, is given as:

$$H_{radio}(f) = H_{int}(f) H_{saw}(f) \tag{1}$$

Other radio components are assumed to have flat frequency response without contributing any distortion. In equation (1), all frequency responses are expressed as complex diagonal matrices with the same frequency bandwidth.

More generally, $H_{radio}(f)$ may have the following form:

$$H_{radio}(f) = H_1(f) \ldots H_n(f) \ldots H_N(f) \tag{2}$$

where N radio devices need to be compensated.

The actual frequency responses of individual system components can be measured using conventional measurement tools, e.g., a spectrum analyzer.

The desired transmitted frequency response, $H_{desire}(f)$, can be determined from the wireless communication system requirements. For example, according to the PWT standard, the desired system frequency response in the baseband is a root raise cosine filter response, i.e.,

$$|H_{desire}(f)| = \begin{cases} 1 & 0 \le f \le (1-\alpha)/2t \\ \sqrt{½(1-\sin[(2\pi f T-\pi)/2\alpha])} & (1-\alpha)/2T \le f \le (1+\alpha)/2T \\ 0 & f \ge (1+\alpha)/2T \end{cases} \qquad (3)$$

with $\alpha=0.5$. According to the IS 136 Standard, $\alpha = 0.35$.

From Figure 4, it is evident that the following relationship should be maintained for imperfect radio characteristics to be properly compensated:

$$H_{comp}(f)H_{radio}(f) \cong H_{desire}(f) \qquad (4)$$

A possible solution for $H_{comp}(f)$ can be:

$$H_{comp}(f)=H^{H}_{radio}(f)H_{radio}(f))^{\cdot}H^{H}_{radio}(f)H_{desire}(f) \qquad (5)$$

or

$$H_{comp}(f)=H^{+}_{radio}(f)H_{desire}(f) \qquad (6)$$

where $H^{H}_{radio}(f)$ is the Hermitian (complex conjugate transpose) of $H_{radio}(f)$, and '+' represents a pseudo-inverse operation. If $H_{radio}(f)$ is of full rank, equation (6)

becomes:

$$H_{comp}(f)=H_{radio}^{-1}(f)H_{desire}(f) \tag{7}$$

According to the first embodiment, the filter coefficients of the digital compensation filter can be obtained from the compensation frequency response $H_{comp}(f)$. An input radio signal is filtered through the digital compensation filter to reduce distortion.

According to a second embodiment of the present invention, radio distortion is digitally compensated for by employing an adaptive filtering technique in which a gradient descent algorithm is used to obtain an adaptive compensation impulse response while minimizing a cost function.

Figure 5 illustrates a technique for digital compensation using an adaptive algorithm according to the second embodiment of the present invention. Referring to Figure 5, $h_{desire}(i)$, where $i=0,1,2...I-1$, and $h_{radio}(j)$, where $J=0,1,2,...J-1$, represent the desired system impulse response and the actual system impulse response, respectively. "I" and "J" represent the number of taps of $h_{desire}(i)$ and $h_{desire}(j)$. The desired system impulse response, $h_{desire}(i)$, and the actual system impulse response, $h_{radio}(j)$ can be obtained from the desired system frequency response, $H_{desire}(f)$, and the actual system frequency response, $H_{radio}(f)$, respectively, by applying an inverse-Z transform. Alternately, $h_{desire}(i)$ can be determined from the wireless communication system requirements. Also, $h_{radio}(j)$ can be obtained by using conventional measurement tools, such as a spectrum analyzer and a network analyzer, to measure the actual impulse response of individual components in the system contributing to distortion and then convolving the individual actual impulse responses.

An adaptive algorithm is used to form the adaptive compensation impulse response. As shown in Figure 5, the adaptive compensation impulse response $w_m(k)$ is applied to the radio signal to compensate for distortion. The order "m" of the adaptive compensation impulse response $w_m(k)$ can be selected as desired.

The cost function in the adaptive system is defined as:

$$J=E\{e^T(k)e(k)\} \tag{8}$$

where "E" is an expectation operator, "^{T}" is a vector or matrix transpose operator, and "k" is a sample index with k=1,2,3,... The function e(k) represents the error between the desired output signal d(k) and the actual output signal y'(k), i.e.,

$$e(k)=d(k)-y'(k) \tag{9}$$

where

$$y'(k)=x(k)\otimes w_m(k)\otimes h_{radio}(j) \tag{10}$$

and

$$d(k)=x(k)\otimes h_{desire}(i) \tag{11}$$

where "$\otimes$" represents a convolution operation.

Preferably, an adaptive algorithm is selected to minimize the cost function of the adaptive system. Minimizing the cost function through the adaptive process causes the adaptive compensation impulse response to converge to an optimal solution. While various adaptive algorithms can be used, a least mean square (LMS) algorithm is described here.

Figure 6 illustrates an implementation of the adaptive system shown in Figure 5. Referring to Figure 6, the adaptive compensation impulse response can be obtained by the following updating equation:

$$w_m(k+1)=w_m(k)-\mu\nabla(k) = w_m(k)+\mu\, 2r^T(k)e(k) \tag{12}$$

where μ is a convergence parameter that determines the stability and convergence speed of an adaptive process, and $\nabla(k)$ is an instantaneous gradient estimate of the cost function with respect to adaptive compensation impulse response, i.e.,

2

$$\nabla(k)=\frac{\partial e^2(k)}{\partial w_m(k)}=2e(k)\frac{\partial e(k)}{\partial w_m(k)}=-2r^T(k)e(k) \tag{13}$$

The parameter $^T(k)$ corresponds to the filtered input signal vector having the same dimensions as the adaptive compensation impulse response $w_m(k)$. Each component of $^T(k)$ is a convolution of the input reference sequence x(k) and the actual radio impulse response, $h_{radio}(j)$.

According to the second embodiment, the filter coefficients of the digital compensation filter can be obtained from the adaptive compensation impulse response $w_m(k)$ once it converges to an optimal solution. An input radio signal is filtered through the digital compensation filter to reduce distortion.

Although in Figures 5 and 6 the adaptive compensation impulse response is applied using a Finite Impulse Response (FIR) filter, the method according to this embodiment of the present invention can be employed with various filter types, including Infinite Impulse Response (IIR) filters and lattice filters.

Also, although the second embodiment has been described with reference applications in a time domain, the adaptive process may also be applicable in a frequency domain.

According to exemplary embodiments of the present invention, transmission quality and modulation accuracy are improved by employing digital compensation in a digital modem in the transmission path of a wireless communication system. Transmission quality and modulation accuracy in the transmission path can be categorized by a series of parameters. One important parameter is DVEM (Differential Vector Error Magnitude) which measures the differential error for a non-coherent differential demodulator, or EVM (Error Vector Magnitude) for a coherent demodulator.

Exemplary radio transmission performance results were obtained using the digital compensation method and apparatus according to the present invention. Using an Anritsu 8604A Transmitter Tester, improvements of approximately 2.74% DVEM including 1.84% magnitude error and 1.16° (16%) phase error, and 8.17 dB I/Q offset were measured. Using an HP 89441 Vector Analyzer, improvements of approximately 2.21% EVM including 1.81% magnitude error and 0.81° (16.46%) phase error, and 5.74 dB I/Q offset were measured. As can be seen from these measurements, the application of digital compensation shows a significant improvement in signal quality. In addition to these improvements, better separated and more stable constellation points were also observed.

In summary, according to the present invention, a method and apparatus are provided for digital compensation which improve modulation accuracy and transmitted signal quality substantially without introducing additional cost. Without introducing additional analog components and modifying analog circuit designs, the present invention offers an attractive and cost effective solution for radio distortion compensation. Furthermore, no additional digital hardware resources are required other than that already existing in a digital modem.

Although the methods described above are for low-tier PCS wireless communication applications, the same principle can be applied to cellular, satellite, and other wired or wireless telecommunication systems. Furthermore, although the embodiments above have been described with reference to compensating for distortion in a transmission path, the present invention is also applicable for compensating for distortion caused by other portions of a wireless communication system, such as the receiving path.

While the foregoing description includes numerous details and specificities, it is to be understood that these are for purposes of explanation only. Many modifications will be readily apparent to those of ordinary skill in the art which are clearly within the and scope of the invention, as defined by the following claims and their legal equivalents.

WHAT IS CLAIMED IS:

1. In a digital modem in a wireless communication system, a method of digitally compensating for radio distortion in a radio signal, the method comprising the steps of:

determining an actual frequency response of components in the system contributing to distortion;

multiplying an inverse of the actual frequency response and a desired system frequency response to produce a compensation frequency response; and

applying the compensation frequency response to the radio signal.

2. The method of claim 1, wherein the radio distortion is caused by components in a transmission path.

3. The method of claim 1, further comprising the steps of storing the compensation frequency response in a memory and downloading the compensation frequency response.

4. The method of claim 1, further comprising the step of implementing the compensation frequency response in hardware components.

5. In a digital modem in a wireless communication system, a method of digitally compensating for radio distortion in a radio signal, the method comprising the steps of:

determining an actual impulse response of components in the system contributing to distortion;

applying the actual impulse response to an input reference signal to produce an actual output signal;

applying a desired system impulse response to the input reference signal to produce a desired output signal;

subtracting the actual output signal from the desired output signal to produce an error signal;

applying an adaptive algorithm to the error signal to produce an adaptive compensation impulse response; and

applying the adaptive compensation impulse response to the radio signal when the adaptive compensation impulse response converges to an optimal value.

6. The method of claim 5, wherein the radio distortion is caused by components in a transmission path.

7. The method of claim 5, further comprising the step of storing the adaptive compensation impulse response in a memory and downloading the adaptive compensation impulse response.

8. The method of claim 5, further comprising the step of implementing the adaptive compensation impulse response in hardware components.

9. The method of claim 5, wherein the adaptive algorithm is a least mean squares algorithm.

10. In a digital modem in a wireless communication system, an apparatus for digitally compensating for radio distortion, the apparatus comprising:

a storage device for storing a compensation frequency response corresponding to a multiplication of an inverse actual frequency response of components in the system contributing to distortion with a desired system frequency response; and

a digital filter for applying the compensation frequency response to the radio signal to compensate for the radio distortion.

11. The apparatus of claim 10, wherein the radio distortion is caused by components in a transmission path.

12. The apparatus of claim 10, wherein the storage device comprises a memory, and the compensation frequency response is downloaded from the memory into the digital filter.

13. The apparatus of claim 10, wherein the storage device comprises hardware components.

14. In a digital modem in a wireless communication system, an apparatus for digitally compensating radio distortion, the apparatus comprising:

a storage device for storing an adaptive compensation impulse response, the adaptive compensation impulse response corresponding to the application of an adaptive algorithm to a difference between an actual output signal produced by the application of an actual impulse response of components in the system contributing to distortion to an input reference signal and a desired output signal produced by the application of a desired system impulse response to the input reference signal; and

a digital filter for applying the adaptive compensation impulse response to the radio signal, when the adaptive compensation impulse response converges to an optimal solution.

15. The apparatus of claim 14, wherein the radio distortion is caused by components in the transmission path.

16. The apparatus of claim 14, wherein the storage device comprises a memory, and the adaptive compensation impulse response is downloaded from the memory into the digital filter.

17. The apparatus of claim 14, wherein the storage device comprises hardware components.

18. The apparatus of claim 14, wherein the adaptive algorithm is a least mean squares algorithm.

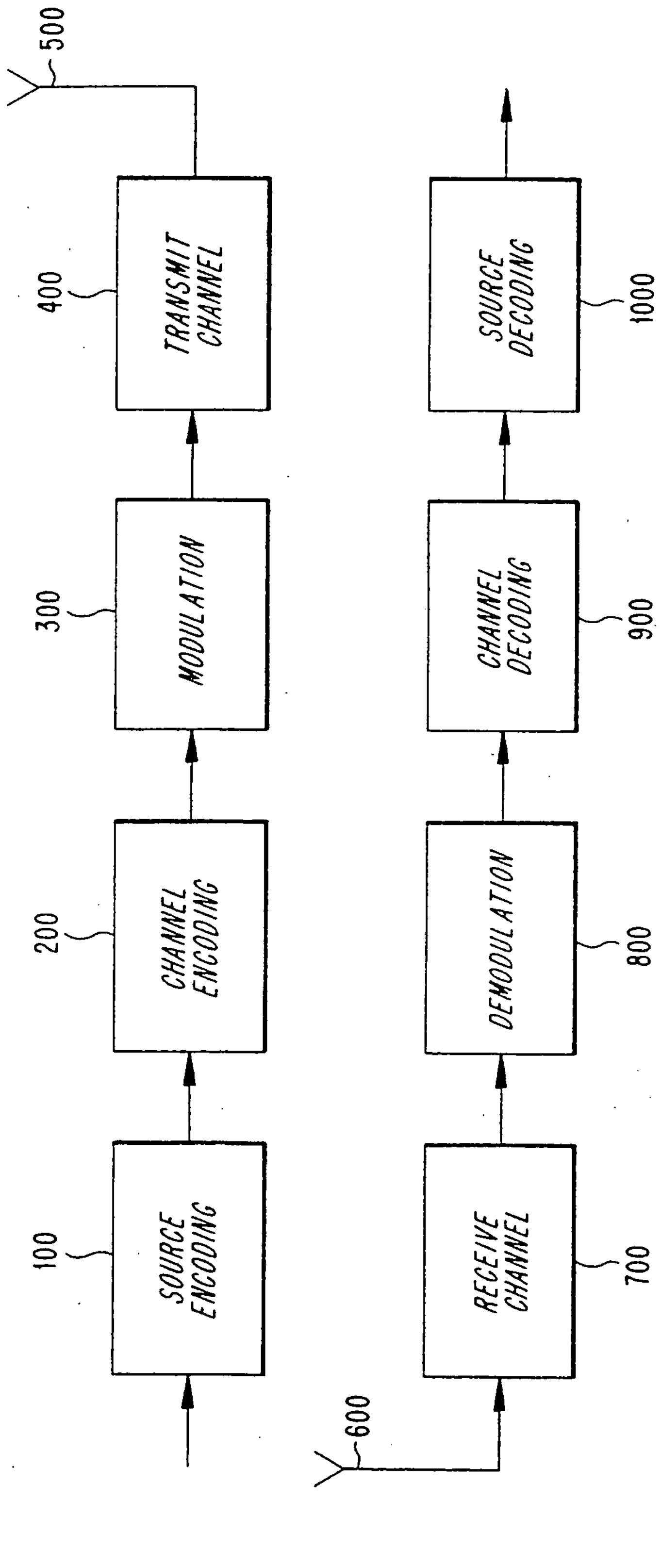

SOURCE ENCODING
100
CHANNEL ENCODING
200
MODULATION
300
TRANSMIT CHANNEL
400
500
600
RECEIVE CHANNEL
700
DEMODULATION
800
CHANNEL DECODING
900
SOURCE DECODING
1000

FIG. 1

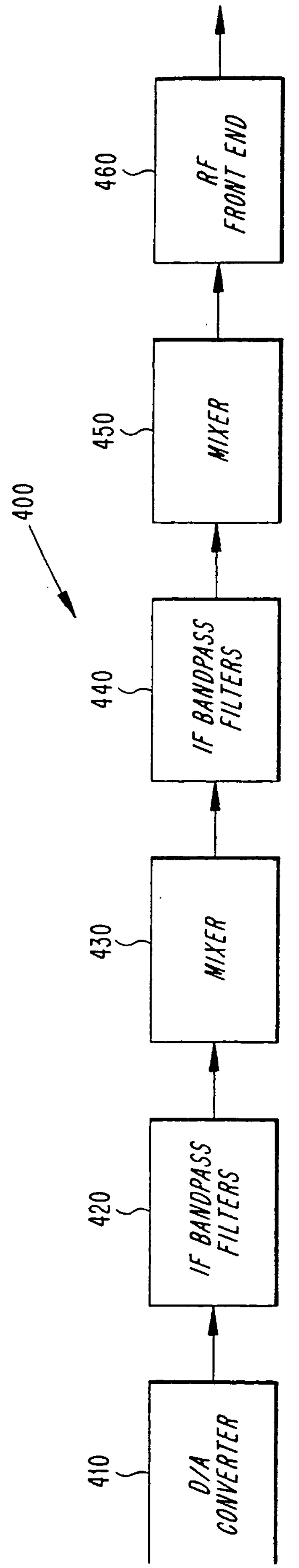
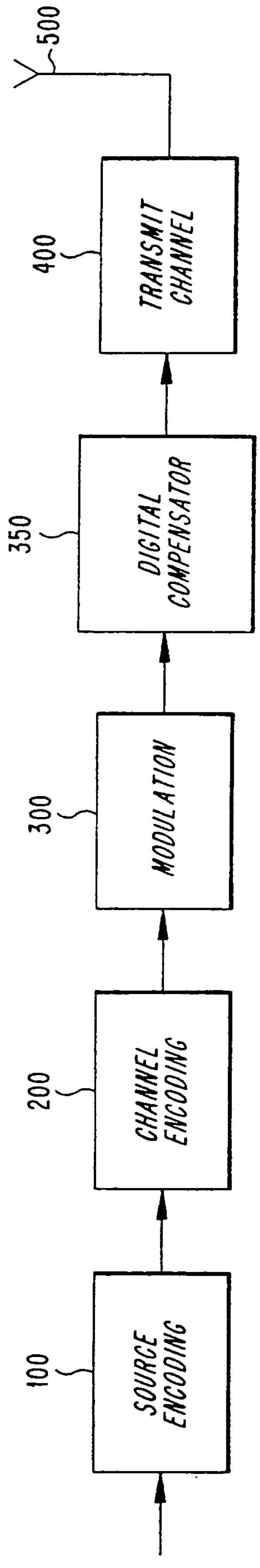

400
410
D/A CONVERTER
420
IF BANDPASS FILTERS
430
MIXER
440
IF BANDPASS FILTERS
450
MIXER
460
RF FRONT END

FIG. 2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CHANNEL ENCODING
300
MODULATION
350
DIGITAL COMPENSATOR
400
TRANSMIT CHANNEL
500

FIG. 3

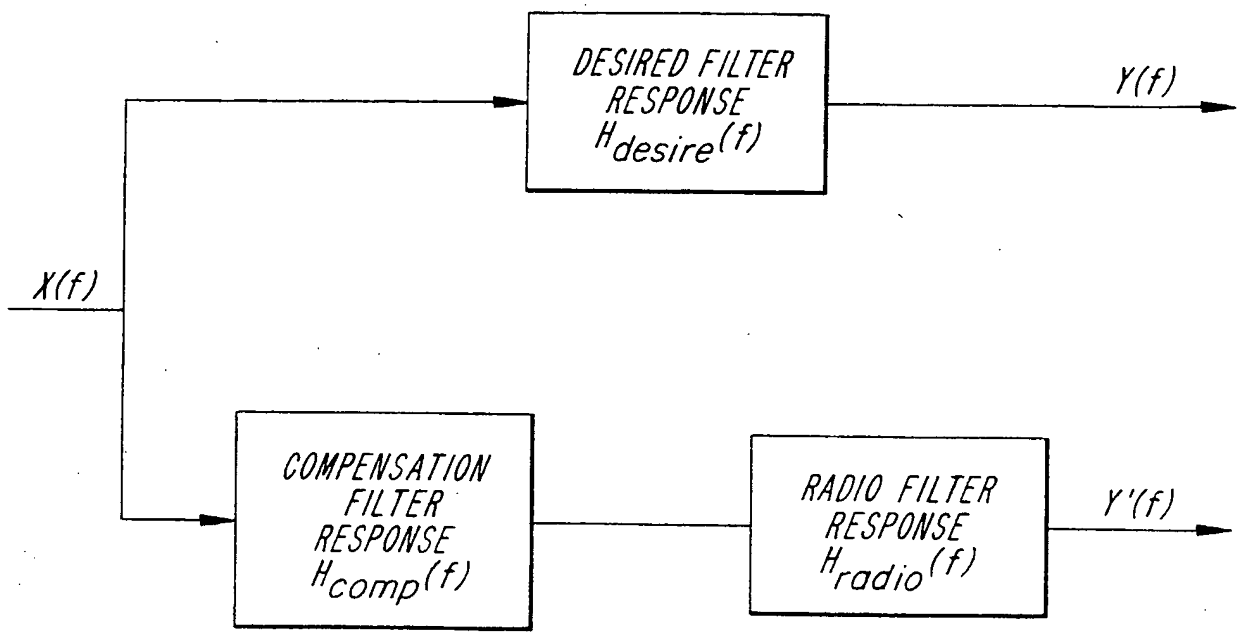
DESIRED FILTER RESPONSE $H_{desire}(f)$
Y(f)
X(f)
COMPENSATION FILTER RESPONSE $H_{comp}(f)$
RADIO FILTER RESPONSE $H_{radio}(f)$
Y'(f)

FIG. 4

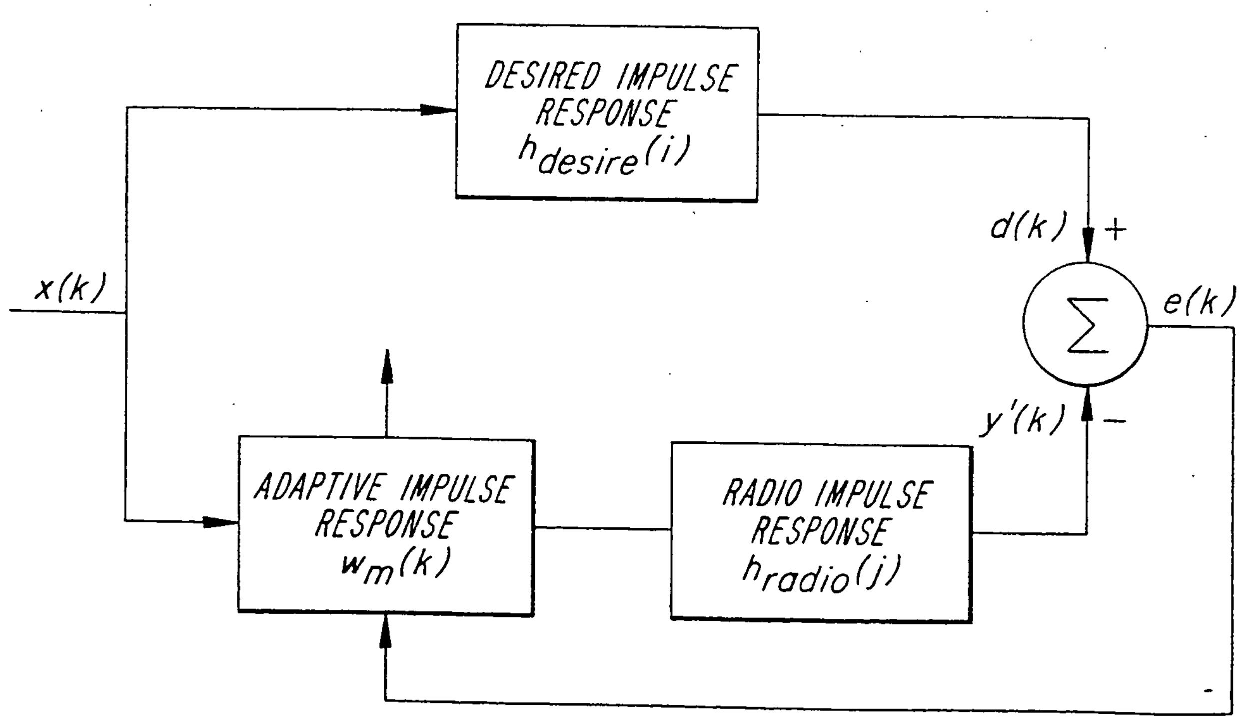
DESIRED IMPULSE RESPONSE $h_{desire}(i)$
d(k)
+
x(k)
e(k)
y'(k)
−
ADAPTIVE IMPULSE RESPONSE $w_m(k)$
RADIO IMPULSE RESPONSE $h_{radio}(j)$

FIG. 5

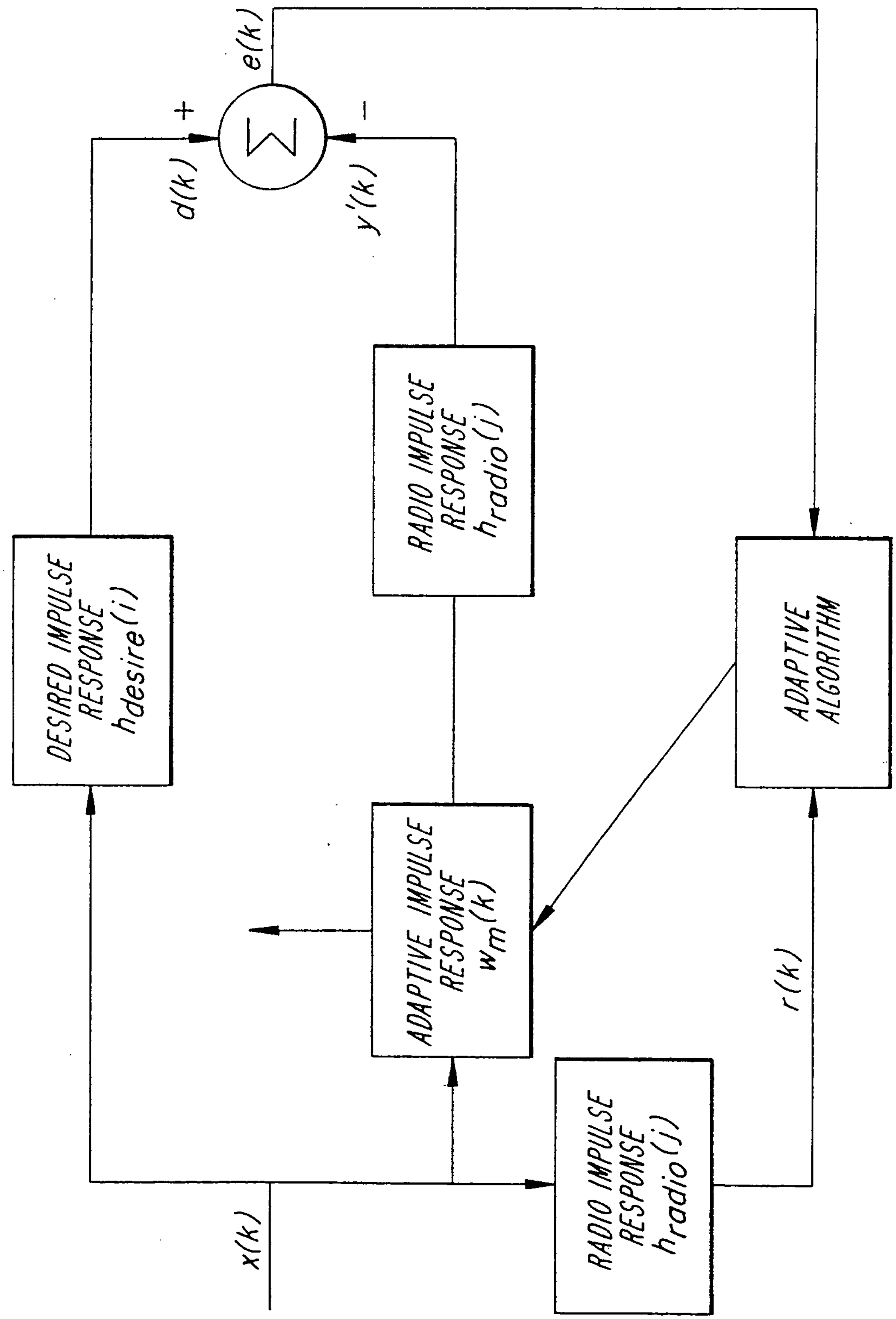
x(k)
DESIRED IMPULSE RESPONSE hdesire(i)
d(k)
+
Σ
-
e(k)
y'(k)
RADIO IMPULSE RESPONSE hradio(j)
ADAPTIVE IMPULSE RESPONSE wm(k)
RADIO IMPULSE RESPONSE hradio(j)
r(k)
ADAPTIVE ALGORITHM

FIG. 6

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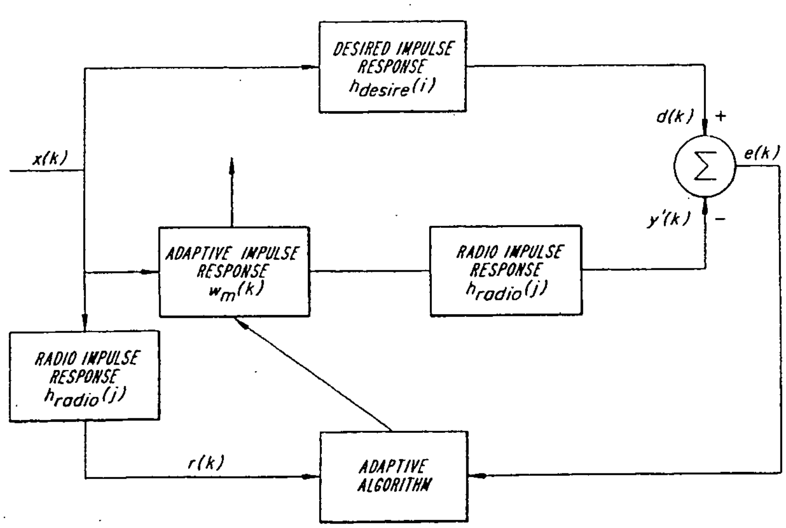

(57) Abstract

Radio distortion in a radio signal is compensated for in a digital modem in a wireless communication system. An actual frequency response of components in the wireless communication system contributing to distortion is determined. The inverse of the actual frequency response is multiplied with an ideal frequency response of the wireless communication system to produce a compensation frequency response. The compensation frequency response is applied to the radio signal to compensate for radio distortion. Alternately, an actual impulse response of components in the wireless communication system contributing to distortion is determined. The actual impulse response is convolved with an input reference signal to produce an actual output signal. The ideal impulse response is convolved with the same input reference signal to produce a desired output signal. The actual output signal is subtracted from the desired output signal to produce an error

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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/12466

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H04B1/04 H04L27/36

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 H04L H04B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

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A		10,11,13

X	FORNEY JR G D ET AL: "COMBINED EQUALIZATION AND CODING USING PRECODING" IEEE COMMUNICATIONS MAGAZINE, vol. 29, no. 12, 1 December 1991, pages 25-34, XP000287979 see page 29, line 24 - line 30; figure 5	1,2,4
A		10,11,13

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[X] Further documents are listed in the continuation of box C.

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Date of the actual completion of the international search	Date of mailing of the international search report
15 January 1999	22 JAN 1999

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/12466

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

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